Physics at $\gamma\gamma$ and γe colliders

Ilya F. Ginzburg[a]

[a]Sobolev Institute of Mathematics, Siberian Branch of RAS,
Prosp. ac. Koptyug, 4, 630090 Novosibirsk, Russia

I discuss, what really new could give Photon Colliders ($\gamma\gamma$ and $e\gamma$) after LHC and e^+e^- Linear Collider operations.

1. Possible scenarios

• The developed physical programs of new machines are based on the idea, that *the Nature is so favorable to us that it has placed the essential fraction of new particles within the LHC operation domain.* Moreover, in these programs we believe, that new particles or interactions belong to one of the known sets and we consider an opportunity to see them. Together with Higgs boson (or bosons) in the one or two doublet $\mathcal{SM}$, the expected most probable variants are SUSY–$\mathcal{MSSM}$, leptoquarks, WW or WZ resonances, compositeness, effects from large extra dimensions,... Such type assumption is necessary component of the physical program of the LHC, where the discovery of something unexpected is hardly probable.

Main goal of the LHC is a discovery of some of enumerated particles or effects. The e^+e^- Linear Colliders should measure parameters of new particles and corresponding couplings with high accuracy. Some unexpected new particles will be seen here via the threshold behaviour in two jet or lepton production. The Photon Colliders in this approach are considered as the machines for the precise study of QCD and cross check of couplings measured earlier.

• In this approach one forget some problems of the $\mathcal{SM}$ (including its foundation). The solutions (still unknown) could be tested with the aid of Photon Colliders only.

• We should be ready to meet the opposite opportunity: *no new particles will be discovered at LHC, except Higgs boson* ($\mathcal{SM}$ or $2\mathcal{HDM}$ or $\mathcal{MSSM}$). In this case Photon Colliders could give the best key to the discovery of a New Physics.

• In this report we consider this very opportunity. We assume that either New Physics differs strong from the expected variants or new particles in the one of expected variant are very heavy (except Higgs boson(s)) or some difficult opportunity within $\mathcal{MSSM}$ is realized (see e.g. [1]).

2. Photon Colliders. Main features

The future Linear Colliders would form the complexes including both e^+e^- collider mode and Photon collider mode ($\gamma\gamma$ and γe) [2,3]. This photon mode is based on the e^+e^- one with electron energy E and luminosity $\mathcal{L}_{ee}$. Here I present its main characteristics *assuming no special efforts in optimization of photon mode at the initial stages of acceleration* [2,3].

- Characteristic photon energy $E_\gamma \approx 0.8E$.
- Annual luminosity $\mathcal{L}_{\gamma\gamma} \approx 100$ fb^{-1} ($\mathcal{L}_{\gamma\gamma} \approx 0.2\mathcal{L}_{ee}$).
- Mean energy spread $< \Delta E_\gamma > \approx 0.07 E_\gamma$.
- Mean photon helicity $< \lambda > \approx 0.95$ with easily variable sign. One can transform this polarization into the linear one [4].
- There are no special reasons against observations at small angles except non–principal technical details of design.
- The conversion region is γe collider with c.m.s. energy about 1.2 MeV but with annual luminosity $\sim 10^6$ fb^{-1}!

Below we denote by λ_i mean degree of the photon circular polarization (helicity) and by ℓ_i mean degree of their linear polarization, ϕ is the angle be-

tween directions of these linear polarizations for opposite photons, $y_i = E_{\gamma i}/E$.

Approximate photon spectra [5]. The luminosity distribution in the effective $\gamma\gamma$ mass has usually two well separated peaks:
a) high energy peak with mentioned mean energy spread 7% and integrated luminosity $0.2\mathcal{L}_{ee}$;
b) wide low energy peak. The last depends strongly on details of design, it is unsuitable for the study of New Physics phenomena.

The form of high energy peak depends on the reduced distance between conversion and interaction points ρ. At $\rho = 0$ separation of peaks is practically absent. In the modern projects $\rho \approx 1$. In this case peaks are separated well, the high energy peak contains about 30 % of geometrical luminosity and 80 % from luminosity of peak at $\rho = 0$. At $\rho^2 < 1.3$ and the ellipticity of beam $A > 1.5$ the high energy peak is independent on A (usually $A \gg 1$). In this region the form of high energy peak is approximated with high precision by a convolution of two effective photon spectra with functions $\tilde{F}(y, \rho)$ written in ref. [5]

$$d\mathcal{L} = \tilde{F}(y_1, \rho)\tilde{F}(y_2, \rho) dy_1 dy_2 \,. \qquad (1)$$

3. Higgs window to a New Physics

The basic point here is the opportunity to measure the two–photon width of the $\mathcal{MSM}$ Higgs boson with accuracy 2 % [6] (one can hope to improve this accuracy since the used luminosity integral 30 fb^{-1} corresponds to only three month operations).

• Let us first talk about the opportunity that some of the discussed scenarios ($2\mathcal{HDM}$, $\mathcal{MSSM}$) is realized, but new particles are heavier than those observable at the LHC (decoupling regime) with two variants:

1. *Strong decoupling.* The additional Higgs bosons $H,\ A,\ H^{\pm}$ are also very heavy.
2. *Weak decoupling.* The additional Higgs bosons $H,\ A,\ H^{\pm}$ are lighter than 400 GeV.

We distinguish the following variants of $\mathcal{SM}$ or its extensions:
⋆ $\mathcal{SM}$ with one Higgs boson doublet — $\mathcal{MSM}$;
⋆ $\mathcal{SM}$ with two Higgs boson doublet — $2\mathcal{HDM}$, or its SUSY extension — $\mathcal{MSSM}$ in the decoupling regime.
In this regime the difference between the $\mathcal{MSSM}$ and the $2\mathcal{HDM}$ in the $\mathcal{MSSM}$ like variant (at $M_{H^\pm}^2 \approx \lambda_5 v^2$) is hardly observable. So we denote usually both cases as $\mathcal{MSSM}$. We denote by $2\mathcal{HDM}$ only its general variant with $M_{H^\pm}^2 \gg \lambda_5 v^2$. Our discussion below is based on the results of Refs. [7,8].

The studies at the LHC could give us some coupling constants of the Higgs boson with a matter (quarks, leptons, W and Z) with accuracy about 10 %. The measurements at e^+e^- Linear Collider will improve accuracy to the level of about 1 %. The deviation of these couplings from their $\mathcal{MSM}$ values could be considered as a signal for realization of a $2\mathcal{HDM}$ or $\mathcal{MSSM}$. The measurement of the two–photon width of a (lightest) Higgs boson allows to separate the general $2\mathcal{HDM}$ from the $\mathcal{MSSM}$. The additional measurement of a $HZ\gamma$ coupling in the $e\gamma \to eH$ process [9,10] could support this differentiation.

We show this for the difficult enough case. Let the measured couplings of the Higgs boson with a matter are given by the $\mathcal{MSM}$. The same values can be obtained in the $2\mathcal{HDM}$ or $\mathcal{MSSM}$ at $\beta - \alpha = \pi/2$. In the $H\gamma\gamma$, $HZ\gamma$ widths effects of W and t quark loops are of opposite sign. That is why the effect of very heavy charged Higgses is enhanced here up to about 13% in the general $2\mathcal{HDM}$. This difference will be seen good even in the case of strong decoupling. In the $\mathcal{MSSM}$ this effect reduces to a few percent level (just as the effect of heavy superparticles) — depending of the mass of these particles.

Therefore the measurement of the Higgs boson $\gamma\gamma$ width with 2 % accuracy could answer which model is realized — general $2\mathcal{HDM}$ or $\mathcal{MSSM}$. And one can get this answer before the discovery of superpartneurs. This measurement could differentiate general $2\mathcal{HDM}$ from $\mathcal{MSM}$ together with $\mathcal{MSSM}$ at $\beta - \alpha = \pi/2$. The discrimination of the $\mathcal{MSSM}$ from the $\mathcal{MSSM}$ like $2\mathcal{HDM}$ needs higher precision in the measuring of the discussed width.

In the weak decoupling case the additional measurements of $H\gamma\gamma$, $A\gamma\gamma$ couplings in the $\gamma\gamma$ collisions, $HZ\gamma$, $AZ\gamma$, $H^-W^-\gamma$ couplings in the

γe collisions would be very useful to discriminate the discussed opportunities.

• Let the New Physics is different from the discussed models. When the collision energy is below scale of New Physics Λ, last manifests itself via *anomalies* in the interactions of known particles. In this case **Photon Colliders provide the best place for discovery of this New Physics and for understanding it.** Indeed the $H\gamma\gamma$, $H\gamma Z$,... vertices in the $\mathcal{SM}$ are one–loop effects. Therefore the relative value of anomalies is enhanced here in comparison with other interactions.

Together with the $\mathcal{SM}$ effects the above anomalies are described by an Effective Lagrangian relevant photon collisions:

$$\begin{aligned}\mathcal{L}_{H\gamma} = \frac{G_\gamma H F^{\mu\nu} F_{\mu\nu}}{2v} + \frac{G_Z H F^{\mu\nu} Z_{\mu\nu}}{v} + \\ \frac{\tilde{G}_\gamma H F^{\mu\nu} \tilde{F}_{\mu\nu}}{2v} + \frac{\tilde{G}_Z H \tilde{F}^{\mu\nu} Z_{\mu\nu}}{v} \,. \\ G_i = \frac{\alpha \Phi_i^{SM}}{4\pi} + \theta_i \frac{v^2}{\Lambda_i^2} \,, \quad (i = \gamma \,,\; Z) \,.\end{aligned} \tag{2}$$

Here $Z_{\mu\nu}$, $F_{\mu\nu}$ and $\tilde{F}_{\mu\nu}$ are standard field strength tensors, $v = 246$ GeV. The values Φ_i^{SM} are well known ($|\Phi_i| \sim 1$). For the $\mathcal{CP}$ even case $\tilde{G}_i = 0$, $\theta_i = \pm 1$. For the $\mathcal{CP}$ odd case all quantities θ_i, $\tilde{\theta}_i$ can be complex, $\theta_a = e^{i\phi_a}$.

The $\mathcal{CP}$ odd anomalies manifest itself in the polarization asymmetry in the production $\gamma\gamma \to H$, $e\gamma \to eH$. In particular, for the $\gamma\gamma \to H$ process we have [13]

$$\begin{aligned}&< \sigma > (\lambda_i, \ell_i, \psi) = < \sigma^{SM} >_{np} \frac{T(\lambda_i, \ell_i \psi)}{|G_\gamma^{SM}|^2}; \\ &T(\lambda_i, \ell_i, \psi) = |G_\gamma|^2 (1 + \lambda_1 \lambda_2 + \ell_1 \ell_2 \cos 2\psi) \\ &\quad + |\tilde{G}_\gamma|^2 \, (1 + \lambda_1 \lambda_2 - \ell_1 \ell_2 \cos 2\psi) \\ &+ 2Re(G_\gamma^* \tilde{G}_\gamma)(\lambda_1 + \lambda_2) + 2Im(G_\gamma^* \tilde{G}_\gamma) \ell_1 \ell_2 \sin 2\psi \,.\end{aligned} \tag{3}$$

Similar equations were obtained for the $e\gamma \to eH$ process and $HZ\gamma$ anomalies. The sensitivity of the corresponding experiments to the scale of New Physics was studied in Refs. [9–13].

4. Gauge boson physics

• In the discussed energy range the New Physics effects will be seen as some deviations from the prediction of $\mathcal{SM}$. These deviations can be described by anomalies in the Effective Lagrangian $\mathcal{L}_{eff}$. There are many anomalies of dimensions 6 and 8 relevant to the gauge boson interactions ($\mathcal{CP}$ even and $\mathcal{CP}$ odd). Each process reacts for several of them. The separate extraction of different anomalies is difficult for the e^+e^- mode with only one well measurable process $e^+e^- \to W^+W^-$. (The γWW and ZWW vertexes enter this process simultaneously.)

In these problems the potential of the Photon Collider is exceptional. Indeed, large variety of the processes with the production of gauge boson will be observed here with both high purity and counting rate (millions or hundred thousands events per year) ($\gamma\gamma \to W^+W^-$, $e\gamma \to W\nu$, $\gamma e \to eWW$, $\gamma e \to \nu WZ$, $\gamma\gamma \to WWZ$, $\gamma\gamma \to WWWW$, $\gamma\gamma \to WWZZ$, $\gamma e \to \nu e^+e^- W$, ...). This large variety allows to separate different anomalies. For example, one can realize such a program: First, to extract γWW anomalies from $\gamma e \to \nu W$ process. After that, to extract ZWW anomalies from $e^+e^- \to W^+W^-$ process. Last, to extract $\gamma\gamma WW$ anomaly from $\gamma\gamma \to W^+W^-$. In the same way the process $\gamma e \to eWW$ allows to study anomaly γZWW.

The study of some separate distributions in the specific regions of parameter space can enhance effect of some anomalies (in comparison with the entire cross section). For example, the total cross section of the process $\gamma e \to eWW$ is determined mainly by effect of $\gamma\gamma \to W^+W^-$ subprocess, the $Z\gamma \to WW$ subprocess become very essential in the cross section of this process, given at the transverse momentum of an electron $p_\perp > 30$ GeV; the polarization asymmetry is sensitive to the possible $\mathcal{CP}$ odd anomalies.

• The dynamical $\mathcal{SU}2 \otimes \mathcal{U}1$ symmetry breaking is also considered often. Here this breaking is caused the strong interaction of W bosons (longitudinal components) — instead of Higgs bosons at $E \gtrsim 4\pi v \approx 3$ TeV. At lower energies amplitudes differ weakly from their $\mathcal{SM}$ values.

The γe collider allows study this strong interaction at smaller energy. For this goal, one should study the process $\gamma e \to eWW$ and should consider charge asymmetry of produced W's (longitudinally polarized, if possible), caused

interference between t–channel γ/Z exchange diagram and corresponding bremsstrahlung diagram. Even if the cross section itself differs weakly from its $\mathcal{SM}$ value, the value of this asymmetry is $\propto \cos(\delta_0 - \delta_1)$ where δ_i are the phases of strongly interacted WW amplitudes [14].

• The reactions $\gamma\gamma \to W^+W^-$ and $e\gamma \to W\nu$ will give about 10 millions W's per year. It provides an opportunity to measure the corresponding cross sections with two loop accuracy.

The EW theory is the standard QFT based on the whole set of the asymptotical states for the fundamental particles. It is the basis for the construction of perturbation theory with the standard particle propagators. But the fundamental particles of theory (W, Z, H) are unstable. The QFT with unstable fundamental particles is unknown till now. Without such a theory precise description of EW processes is impossible.

From this point of view, the breaking of gauge invariance in the calculations of the processes with gauge boson production (like $e^+e^- \to W^+W^- \to \mu\bar{\nu}q\bar{q}$) is not the main effect but the signal on the unsatisfactory state with EW theory. This signal should be used in the construction of satisfactory scheme.

We hope, that new features of such scheme (as compare with constructed recipes like [15]) will be seen at the expected two–loop accuracy level.

The solution of this problem will be an essential step in the construction of QFT relevant for the description of real world.

• The additional interesting field here is the study of the QCD radiative corrections to the $\gamma\gamma \to W^+W^-$ process in the Pomeron regime (two gluon, etc. exchange between quarks from W decays or in their polarization operator at $S \gg M_W^2$).

That is a large area for new work here.

5. The discovery of new unexpected particles

The experiments at the LHC could discover many expected particles but the discovery here of some unexpected particle is very difficult task. Assuming that the decay products of some unexpected charged particle contain known particles, these new particles can be discovered at Linear Collider in both e^+e^- and $\gamma\gamma$ mode. The higher value of the production cross section in $\gamma\gamma$ mode comparing with the e^+e^- mode compensates difference in the luminosities in these modes. The values of these cross sections depend on s/M^2, charge and spin of produced particle. In the e^+e^- mode the additional dependence on the coupling with Z make difficult an unambiguous restoration of the charge and spin of produced particle from the data. The $\gamma\gamma$ mode is free from this difficulty. Additionally, the polarization dependence is useful to determine spin of produced particle independent on its charge. Near the threshold this cross section in the $\gamma\gamma$ mode is

$$\propto (1 + \lambda_1\lambda_2 \pm \ell_1\ell_2 \cos 2\phi) \tag{4}$$

with sign + for scalars and sign − for spinors.

These cross sections decreases slowly with energy growth. They are high at large enough energies. It allows to study decay products in the region where they don't mix with each other.

6. $\gamma\gamma \to \gamma\gamma$ process for the nonstandard New Physics.

Some authors discuss the cases when this process become observable due to loops with some new particles F. It happens possible if the c.m.s. energy is larger than $2M_F$ (usually much larger). These effects cannot give us new information about the particles F because of the processes like $\gamma\gamma \to F\bar{F}$ have higher cross sections and they observable usually a at lower energy.

So I discuss here only two topics related to the nonstandard New Physics:

⋆ Heavy point–like Dirac monopole.
⋆ Effect of extra dimensions.

In both cases we consider the process much below new particle production threshold. Denoting corresponding mass by M, the cross section can be written in the form

$$\sigma(\gamma\gamma \to \gamma\gamma) = \frac{A}{32\pi s}\left(\frac{s}{4M^2}\right)^4 \tag{5}$$

with specific angular distribution (roughly — isotropic) and polarization dependence. The wide

angle elastic light to light scattering has excellent signature and small QED background.

The observation of strong elastic $\gamma\gamma$ scattering, quickly raising with energy, will be a signal for one of mentioned mechanisms. The study of polarization and angular dependence at photon collider can discriminate which mechanism is working.

• **Point–like Dirac monopole** [16]. The existance of this particle explains mysterious quantization of an electric charge. There is no place for it in modern theories of our world but there are no precise reasons against its existence.

At $s \gg M^2$ the electrodynamics of monopoles is expected to be similar to the standard QED with effective perturbation parameter $g\sqrt{s}/(4\pi M)$ where the coupling constant $g = n/(2e)$. The effect is described by monopole loop. So, the coefficient A in eq. (5) is calculated within QED. It is $\propto g^8$ and depends strongly on the spin of monopole J (just as details of angular and polarization dependence). For example, $A(J = 1)/A(J = 0) \approx 1900$.

The effect can be seen at TESLA500 at the monopole mass $M < 4 - 10$ TeV (depending on monopole spin). Modern limitation obtained at Tevatron is about one order of value lower.

• **Effect of extra dimensions** [17]. Nowadays the scenario is considered where gravity propagates in the $(4 + n)$–dimensional bulk of spacetime, while gauge and matter fields are confined to the (3+1)–dimensional world volume of a brane configuration. The extra n dimensions are compactified with some space scale R that result Kaluza–Klein excitations having masses $\pi n/R$. The corresponding scale M in our world is assumed to be $\sim$ few TeV. The particles of our world interact via the set of these Kaluza-Klein excitations having spin 2 or 0. In this approach all unknown coefficients are accumulated in the definition of M in the equation for the cross section (with $A \sim 1$). The angular and polarization dependence of cross section are also known.

Similar results were obtained for other processes $B\bar{B} \to C\bar{C}$. The two photon final state has the best signature and the lowest $\mathcal{SM}$ background. The two photon initial state has numerical advantage as compare with e^+e^- one.

The limitation for effect of extra dimensions correspond for the Photon Collider based on TESLA500 is $M \approx 2.2$ TeV. It is higher than that observable at the LHC.

7. Axions, etc, ... from the conversion region

Some very light and elusive particles a (axions, majorons,...) are expected in many schemes.

They can be produced in the conversion region, that is the γe collider with $\sqrt{s_{e\gamma_0}} \approx 1.2$ MeV or $\sqrt{s_{\gamma\gamma_0}} \approx 1$ MeV and with annual luminosity about million fb^{-1} [18].

The production processes are

$$e\gamma_0 \to ea\,, \quad \gamma\gamma_0 \to a\,. \tag{6}$$

The angular spread of these a is very narrow and they interact with the matter very weakly.

So, the registration scheme can be of the following type. After the damping of photon beam one should set a lead cylinder of diameter about 3–5 cm and length 300 m $-$ 1 km (within angular spread of produced particles). After that some set of scintillators situated in covered circle with radius about 3 m will fix the most part of products of interaction of this particle with the lead nuclei within the cylinder.

8. Final notes

The schedule in the operations of different modes and energies of a Linear Collider depends on the results of LHC studies. Two variants should be considered:

• Let some new particles (SUSY like) will be discovered at the LHC. In this case the natural continuation of the LC500 program will be LC800 with Photon Colliders after that.

• Let no new particles (except Higgs boson) will be discovered at the LHC. In this case the Photon Collider should operate as soon as possible. For example, the Photon Collider with c.m.s. energy $\sqrt{s} \approx M_h \sim 100 \div 200$ GeV for the study mainly of Higgs boson can be the first stage of entire LC project. The advantages of this way are:

The basic electron energy is lower.

The positron beam is unnecessary.

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